A Compact Realization of Composite Low-pass Filter for Monolithic Microwave Integrated Circuit Applications

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ABSTRACT: A compact realization of composite low-pass filter is presented in this article. The filter is realized using on-chip spiral inductors and metal–insulator–metal capacitors and features an attenuation pole near the cutoff frequency leading to a sharper attenuation response. As well, it offers good matching properties in the passband. Space-mapping-based algorithm is used in the design/optimization of spiral inductors toward achieving high quality factors at the filter cutoff frequency. The realization of the proposed filter is compact in size, suitable for monolithic microwave integrated circuit applications, and exhibit broad upper stopband frequency characteristics. © 2011 Wiley Periodicals, Inc. Int J RF and Microwave CAE 22:147–152, 2012.

Keywords: composite low-pass filter; MIM capacitor; space-mapping; spiral inductor

I. INTRODUCTION

Microwave low-pass filters (LPFs) are essential components for a plethora of applications such as radio frequency (RF) test equipments, wireless communications, radar, microwave imaging, and remote sensing. Modern systems impose stringent requirements on filters such as small size, low insertion loss, and high selectivity. A particularly attractive approach to the design of microwave LPFs that satisfy such stringent requirements and specifications uses composite LPF design [1]. A basic composite LPF consists of identical sections in cascade to form a ladder configuration, where the sections are designed using the image method; here, the number of sections in the ladder network determines the stop band rejection of the filter. It is recalled that such image filters are characterized by their image impedance which is defined as the characteristic impedance of an infinite length transmission line made up identical ladder sections [2]. Recently, a composite LPF having cutoff frequency at 1.5 GHz, and based on microstrip lines, has been described in Ref. 3. This filter suffers from ripples in the passband and occupies large amount of chip area. Further, there is potential for increasing the slope of the transition band as it moves toward the stopband of the filter.

The objective in this article is to realize the well-known composite LPF approach with a desired cutoff frequency using on-chip spiral inductors and metal–insulator–metal (MIM) capacitors suitable for MMIC technology. Here, a recently proposed computer-aided design algorithm [4] based on the method of space-mapping is exploited to rapidly yet accurately optimize on-chip spiral inductors exhibiting high quality factors (Q_s) at the desired cutoff frequency. Compared to previously reported composite LPFs [3, 5], the proposed realization is compact (1.4×0.8 mm^2), exhibits sharper cutoff response with a better rejection band, and has a flat passband with a relatively low insertion loss.

The article is organized as follows. Section II discusses design aspects of composite LPFs. Section III deals with its practical realization and simulated results. Finally, conclusions are given in Section IV.

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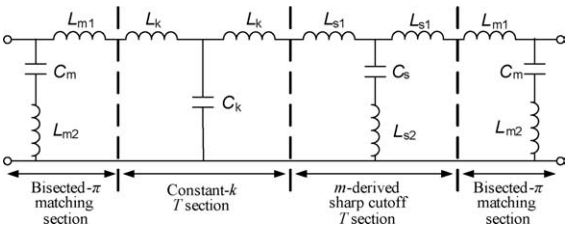


Figure 1 Schematic of a composite LPF.

II. SYNTHESIS OF COMPOSITE LPF

Design of LPFs, which are compact and exhibit sharper attenuation responses, is challenging. Traditional approaches (e.g., Butterworth, Chebyshev, and Elliptic) entail higher-order topologies to achieve a flat passband and sharp attenuation [6, 7] and hence directly contradict the design requirements. A composite LPF can be promising in such challenging scenarios. A composite LPF consists of four sections, namely, a constant-k, an m-derived sharp cutoff, and two m-derived matching sections [1, 2, 8]. Schematic of a composite LPF is depicted in Figure 1. The constant-k section by itself can be used to design either a low-pass or a high-pass filter. However, such filters have two drawbacks. The signal attenuation rate after the cutoff point is not very sharp, and the image impedance is not constant with frequency. We propose that to overcome these drawbacks, m-derived filter sections (a sharp cutoff T section and two matching π sections) are added. We also propose that the aforementioned sections are designed using the image parameter method. The image parameter method is useful for the design of simple filters and provides a link between infinite periodic structure and practical filter design [9].

In the following design example, the cutoff frequency have been arbitrary selected at $f_c = 2.8$ GHz. The proposed design starts with the calculation of constant-k and m-derived T sections, which take into account the desired characteristic impedance R_0 and a parameter m of the T section (which sets the placement of an attenuation pole near f_c). In the proposed design procedure, different values of $m < 0.6$ for the T section are evaluated, leading to the final choice of $m = 0.3$ resulting in a frequency response that meets design specifications. Next, the matching π sections are designed, with their corresponding parameter m set to 0.6 for minimizing the image impedance variation with frequency at the input and output ports. The sections are cascaded to realize a LPF of lower order and smaller size. Such a filter results in a steeper attenuation rate in the transition band (i.e., after the cutoff frequency). The pole can be flexibly adjusted by changing m. Expressions as well as the values of the lumped elements are summarized in Table I. Figure 2 shows the composite LPF design obtained after combining series pairs of inductors and optimizing the lumped element values using Agilent Advanced Design System (ADS) [10].

TABLE I Theoretical Expressions and Values of the Lumped Elements

Sections	Lumped Elements	Expressions	Values
	L	$2R_0/(2\pi f_c)$	5.684 nH
	C	$2/(R_0 2\pi f_c)$	2.274 pF
Constant-k T section	L_k	$L/2$	2.842 nH
	C_k	C	2.274 pF
m-Derived sharp cutoff	L_{s1}	$mL/2$	0.853 nH
($m = 0.3$) T section	L_{s2}	$L(1 - m^2)/(4m)$	4.310 nH
	C_s	mC	0.682 pF
m-Derived matching	L_{m1}	$mL/2$	1.705 nH
($m = 0.6$) bisected-π	L_{m2}	$L(1 - m^2)/(2m)$	3.031 nH
section	C_m	$mC/2$	0.682 pF

$f_c = 2.8$ GHz and $R_0 = 50\ \Omega$.

III. COMPACT REALIZATION USING SPIRAL INDUCTORS AND MIM CAPACITOR

The next step is to realize the filter schematic in Figure 2, in particular, the inductors and the capacitors. Here, we use rectangular spiral inductors and MIM capacitors toward realizing a compact composite LPF. Spiral inductors and MIM capacitors possess relatively lower Qs compared to their distributed counterparts owing to both smaller dimensions and multilevel fabrication processes. To their advantage, on-chip spiral inductors and MIM capacitors are lower cost and have wider bandwidths [11]. The following steps describe the proposed composite LPF realization.

A. Choice of Substrate and Metal Layers

A 300-μm silicon substrate with a dielectric constant of 11.9 and a loss tangent of 0.005 [12], and a 5-μm silicon dioxide with a dielectric constant of 4 and a loss tangent of 0.001, are used as the substrate and the oxide layers, respectively. Two copper metal layers M_1 and M_2 of 1 μm thickness and 5.8×10^7 S/m conductivity are used for the spiral inductor and the underpass, respectively. These metal layers are also used for the MIM capacitor plates. The cross sections and top views of spiral inductors and MIM capacitors are depicted in Figures 3 and 4, respectively.

B. Optimization of spiral Inductors and MIM Capacitors

The objective of this step is to separately realize each of the six inductors and four capacitors with specific values at 2.8 GHz as indicated in Figure 2. Note, at GHz frequencies, eddy currents and self-resonance inside the spiral inductor affects the inductor's performance in terms of both its inductance and Q [13]. As such, accurate design of inductors considering such phenomena demands the use of CPU-expensive electromagnetic (EM) simulations. Our recent space-mapping-based algorithm, which exploits the sequential quadratic programming (SQP) technique for coarse

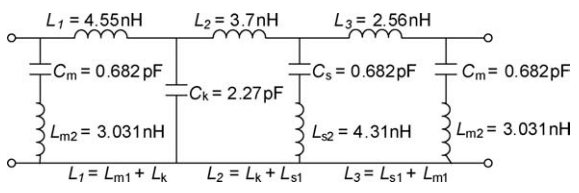


Figure 2 Lumped equivalent circuit prototype of the composite LPF.

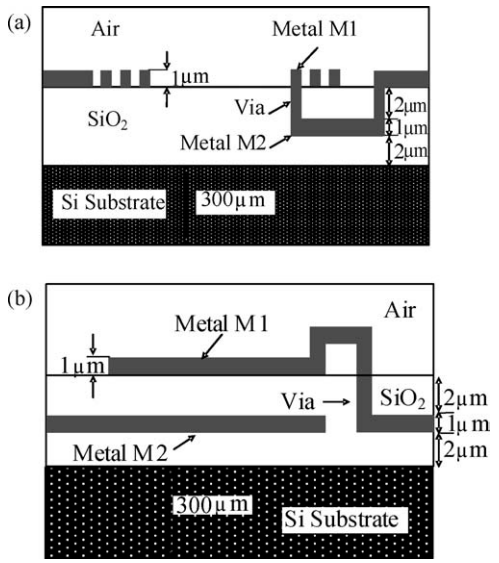


Figure 3 Cross section of (a) spiral inductor and (b) MIM capacitor.

model optimization is applied for the design/optimization of all six inductors of Figure 2 [4]. Starting with desired frequency range and inductance, the algorithm leads to spiral inductor designs with high *Q*s, using minimal amounts of EM data. Considering one inductor at a time, the algorithm first improves the inductor's circuit model, until the circuit model response matches with the EM-simulated response of Zeland IE3D [14]. This is accomplished by iteratively adjusting the preassigned parameters [4].

The next step is to optimize the resulting improved circuit model leading to the specified inductance value at 2.8 GHz. This is achieved by iteratively adjusting the spiral inductor geometry (as the circuit model parameters relate to the inductor geometry). The algorithm leads to a spiral inductor layout offering the desired inductance and an

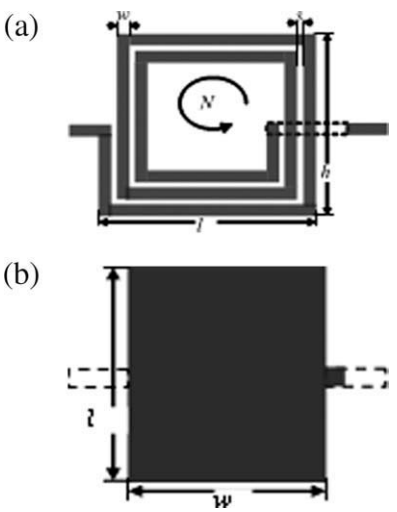
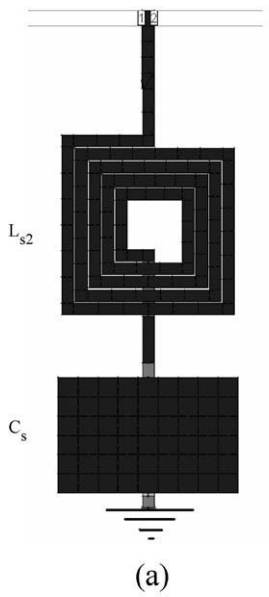


Figure 4 Top view of (a) spiral inductor and (b) MIM capacitor.



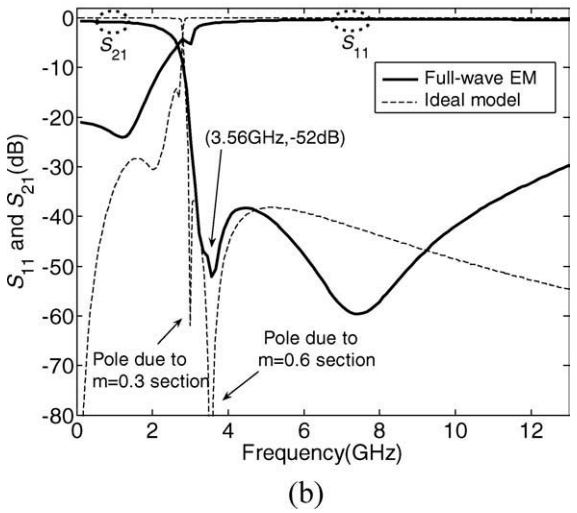


Figure 5 (a) A series LC resonator and (b) its frequency characteristics using EM simulations.

optimal *Q*. In this work, *Q*s of all six spiral inductors are in the [7, 9] range. It is ensured that the self-resonance frequency of each inductor is much higher than 2.8 GHz.

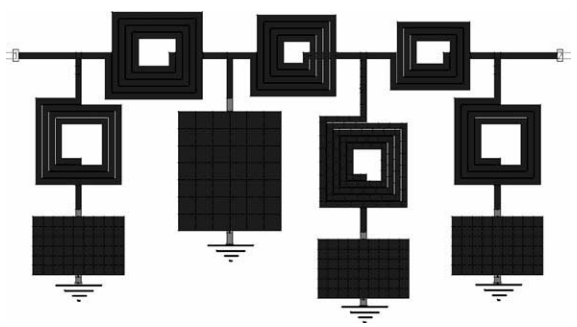


Figure 6 Layout of the proposed composite LPF in Zeland IE3D.

TABLE II Dimensions of Spiral Inductors in the Proposed Composite LPF

Inductors	l (μm)	h (μm)	w (μm)	s (μm)	N
L_1	244	220	15	2	4.5
L_2	215	204	15	2	4.5
L_3	200	172	15	2	3.5
L_{m2}	219	216	15	2	3.5
L_{s2}	231	220	15	2	4.5

The four MIM capacitors are initially designed using semianalytical equations [11], and the initial designs are optimized in Zeland IE3D leading to specified capacitances at 2.8 GHz. To connect all these elements, extra transmission lines are needed in the shunt arms of the circuit. These lines affect the inductance and capacitance values. As such, the dimensions of inductors/capacitors had to be fine-tuned to account for the extra lines.

C. Optimization of Resonators

Series inductor-capacitor (LC) resonators in the shunt arms of the filter require additional fine-tuning by EM simulations to ensure operation at the desired resonant frequencies. For instance, Figure 5(a) shows one of the three LC resonators representing L_{s2} and C_s of Figure 2, which is expected to provide the first pole of the composite LPF at 3 GHz. Figure 5(b) shows resonance of the LC resonator at 2.99 GHz using Zeland IE3D simulations.

IV. RESULTS AND DISCUSSIONS

Finally, all the aforementioned sections are combined to build the complete composite LPF, whose layout is shown in Figure 6. Physical dimensions of inductors/capacitors in the final LPF are tabulated in Tables II and III, respectively. For comparison, ideal ADS simulations and actual Zeland IE3D simulations are presented in Figure 7. EM simulations show a flat response with no ripple, good matching properties, rejection of the attenuated pole as high as 59.5 dB, and low insertion loss in the passband (0.76 dB at 0.19 GHz). The cutoff frequency is 2.6 GHz, and the stopband attenuation is greater than 20 dB over a 12 GHz bandwidth. The slope of S_{21} between cutoff frequency and the first pole is 50 dB/GHz, which is much higher than the 25 dB/GHz slope of the LPF reported in [3]. As well, the proposed filter occupies a compact area of 1.4×0.8 mm^2, which is much smaller than 67×23 mm^2 occupied by the LPF in [3, 5]. As seen in Table IV, there is a reasonable agreement between the performance of the proposed filter and that of its ideal counterpart. Minor discrepancies are due to both parasitic effects and losses of the spiral inductors and MIM capacitors, which are not considered by the ideal model.

TABLE III Dimensions of MIM Capacitors in the Proposed Composite LPF

Capacitors	l (μm)	w (μm)
C_m	230	148
C_k	258	300
C_s	230	150

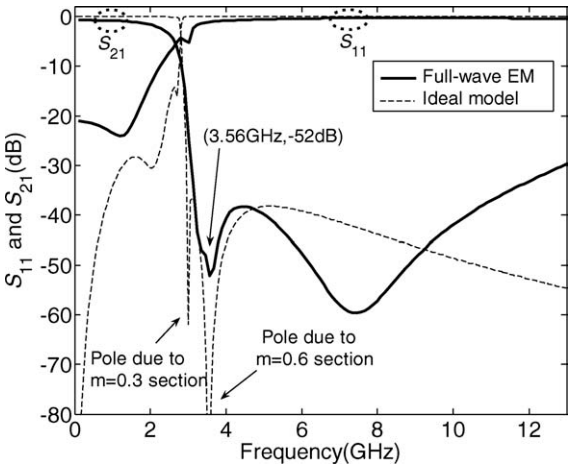


Figure 7 *S*-Parameter responses of the composite LPF obtained from EM simulations and ideal model simulations using Agilent ADS.

TABLE IV Comparison of the Performances of the Proposed Filter Obtained Using Ideal Model and Full-Wave Simulations

	Loss at 0.19 GHz (dB)	f_c (GHz)	f of First Pole (GHz)	Attenuation of First Pole (dB)
Ideal model simulations	0	2.8	3	62
Full-wave EM simulations	0.76	2.6	3.56	52

V. CONCLUSIONS

A composite LPF based on spiral inductors and MIM capacitors for MMIC applications was presented. The realization of the proposed filter with finite frequency transmission zeros that are closely positioned to the passband offers a sharp cutoff response. A flat passband with minimal insertion loss levels and wide rejection band performance is achieved. The overall size of the filter is considerably reduced compared to other filters operating in the same frequency range. A novel procedure has been proposed that allows the design to be scaled up or down for other frequencies. A comparison between EM simulations and ideal model responses has shown reasonable agreement.

The proposed method is advantageous in modern multilayered microwave circuits such as microwave monolithic integrated circuits or low-temperature cofired ceramics technologies leading to compact filters with high selectivity and low insertion loss.

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BIOGRAPHIES

Navid Arbabi received the B.Sc. degree in Electrical Engineering (Electronics) from Ferdowsi University of Mashad, Iran, in 2005, and the M.A.Sc. degree in Electrical and Computer Engineering from Concordia University, Montreal, Canada, in 2008. He joined IDEA (Ajilon Consulting) in 2008, where he works as an IT consultant.

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